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Ranking the criteria for autonomous vehicle adoption from different stakeholders' viewpoints with a grey AHP model

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Abstract
Evaluating the implementation and adoption perspectives of new technologies requires a sophisticated decision-making process. Moreover, multiple groups of stakeholders can be involved in the process, and their aspects should be considered by a decision support methodology. Therefore, this study employs the Grey Analytic Hierarchy Process (grey AHP) to rank the criteria for autonomous vehicle (AV) adoption from various stakeholders' perspectives, such as users, legislators, operators, and manufacturers. The Grey AHP, which integrates grey system theory with the traditional AHP to model uncertainty with interval-based judgments, provides a more robust framework for capturing the variability in expert evaluations. The comprehensive approach of the study integrates EU-based stakeholders' viewpoints, thus providing a balanced framework for understanding the complex trade-offs involved in AV adoption while considering the possible vague evaluations by using grey sets. The analysis reveals that safety is the paramount criterion across all stakeholder groups, as evidenced both by its emergence as the top-ranked factor and by the high combined weight of safety-related criteria. The user group indicates higher willingness and desire reduced fuel consumption and in-vehicle travel time, while ignoring reduction in insurance. For manufacturers, increase in safety criterion stands out, making it by far the most influential factor compared to all other criteria. Similarly, for legislators, increased vehicle and passenger safety criterion emerges as the most influential criterion. In the overall assessment of the results aiming to guide the future development of AV technology, a holistic approach is necessary prioritizing safety, reliability, and affordability, while also addressing emerging issues, such as data privacy and cybersecurity.

Keywords Autonomous vehicles, Grey systems, Grey analytic hierarchy process, Stakeholder analysis

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1 Introduction

Recent advances in artificial intelligence and 5G have accelerated the implementation of autonomous vehicles (AVs). Although fully autonomous traffic [30] will be deployed in the future, the current autonomous driving technology has already realized some features [31]. Following the SAE classification [42] we consider the three primary actors of driving (human, driving automation system, other vehicle systems and components) when defining the automation levels. Based on the classification six levels of automation are defined, namely L0: no driving automation, L1: Driver assistance, L2: Partial driving automation, L3: Conditional driving automation, L4: High driving automation, and L5: Full driving automation. This approach should be applied in the survey design and criteria selection as well as the presentation of the survey objectives to the respondents.

The current paper specifically focuses on AV adoption forecasting and its most significant influential factors [34], which is strongly based on expert knowledge but still exposed to subjectivity concerns [44] mainly due to the uncertain projection of adoption trends of other technologies and sales estimates. The proposed model, which is capable of dealing with uncertainty of expert responses can improve forecasting efficiency [26]. Throughout the whole paper, the term 'implementation' is used in the sense of adoption of AVs.

The process of AV adoption can be accelerated or decelerated by certain criteria and conditions [16] as well as the motivation of some stakeholders involved in the AV industry. A research gap arises when exploring the criteria that might support reaching the totally automatically controlled traffic stage (L5). Since multiple parties (manufacturers, operators, legislators, and users) are involved in this industry and their motivations can be varied [19], the majority of the stakeholders' viewpoints should be examined, and various objectives must be synthesized and cautiously handled.

The preference scoring should be approached in a sophisticated way because of the uncertainty related to future perspectives [55] and the flexible interpretation of the scale used for scoring. Converting the verbal scale of the traditional Analytic Hierarchy Process (AHP) to crisp numbers is especially difficult when it comes to forecasting [17] and when several evaluators struggle to find the correct score of their intentions. This imbalance is often implicit because the participants do not mention it during the survey process; however, ex-post checks reveal that the evaluators were uncertain when selecting a score from the scale [47]. Consequently, the traditional AHP with crisp numbered scale might lead to flawed and untrustworthy outcomes in case of predictive surveys. All these arguments lead to the application of grey methodology and the creation of a specified grey model to investigate the AV criteria from different stakeholders' perspectives.

By employing the Grey Analytic Hierarchy Process (grey AHP) to rank the criteria for AV implementation from different stakeholders' viewpoints, this study offers several key contributions that address existing methodological gaps and enhance the analytical depth of AV evaluation research:

- First, the study strengthens the methodological background by clarifying the limitations of traditional AHP and motivating the adoption of grey AHP. While traditional AHP has been widely used in the literature (e.g., [19]), its reliance on crisp numerical judgments restricts its ability to reflect ambiguity, subjective evaluations, and group decision-making complexities. This study introduces a grey AHP-based framework that integrates grey system theory with the hierarchical structure of AHP, enabling interval-based representations of the judgments that more accurately capture the uncertainty inherent in stakeholder evaluations.
- Second, the study develops a comprehensive multi-stakeholder evaluation model encompassing manufacturers, operators, legislators, and users. The grey AHP approach allows subjective and possibly inconsistent opinions from different stakeholders to be integrated more flexibly and realistically than in traditional AHP. By incorporating preference diversity and uncertainty, the model provides a more holistic understanding of the multidimensional factors shaping AV adoption. This aligns directly with the research questions of the study, which focus on identifying how different stakeholder groups prioritize AV implementation criteria and which criteria emerge as universally influential across these groups.
- Third, the study introduces an enhanced preference aggregation mechanism capable of supporting more adaptive and forward-looking decision-making. Given the rapid and uncertain evolution of AV technologies, the grey AHP model offers policymakers a more robust decision-support structure compared to crisp evaluation tools. The ability to accommodate uncertainty in judgments enables policymakers and industry actors to better anticipate technological shifts and to design flexible strategies for the transition toward higher levels of autonomy.
- Finally, the proposed model enables both holistic and granular assessments of AV implementation. Each stage of the evaluation can be examined separately for each stakeholder group and for each sub-criterion, providing deeper insight into

where perceptions and priorities diverge. The model's structure allows decision-makers to target high-impact areas for improvement rather than relying on broad, undifferentiated interventions. By capturing the grey relationships between criteria, the framework supports more nuanced policy development and contributes to a more strategic and sustainable pathway toward large-scale AV adoption.

Based on the contributions presented above, the following research questions are aimed to be answered by the research.

Q1: How does the created grey AHP model sophisticate the results of the traditional AHP methodology? What is the main difference in preference rankings of the AV implementation items in the two models?

Q2: According to the results of the proposed grey AHP method, what are the priorities of the different stakeholders of the AV industry?

Q3: What conclusions could be drawn and what recommendations be made based on the presented industrial survey?

The following section reviews the relevant literature on AV implementation criteria, potential stakeholder groups, and the application of grey models in expert surveys, particularly for prediction-based decision-making. Next, the grey AHP methodology and the proposed model are introduced to systematically prioritize the criteria from multiple perspectives. The subsequent sections present and analyze the results of a recent survey in detail, followed by a discussion on the implications of the findings and a conclusion addressing the contributions of the applied model to the AV industry.

2 Literature review

2.1 Models for the criteria and stakeholders' objectives

The basic assumption of this research is that the perspectives of the AV development can be determined in a group decision analysis [7] involving relevant stakeholders. These groups' preferences reflect industry needs and potentials while highlighting the most important factors fomenting the progress [32]. Multi-criteria decision-making (MCDM) techniques designed for groups of evaluators are suitable tools to map group preferences and compare stakeholder weightings [48]. In scientific literature, there are some examples applying MCDM to analyze several segments of the AVs. For example, Ghoushchi et al. [15] investigate how the efficiency of AVs can be increased by the integration of artificial intelligence and Internet of Things. Targeting the risks connected to self-driving vehicles, Bakioglu and Atahan, [2] apply a Pythagorean fuzzy set-based model to prioritize the threats connected to eliminating human driving skills from transportation. While Dogan et al. [5] analyze the location selection of automated vehicles by a fuzzy AHP and Technique for Order of Preference by Similarity to Ideal Solution (TOPSIS) model. However, these papers shed light merely on a specific segment or problem of the AV industry; thus, an integrated approach can be identified as a gap in scientific literature.

A more integrated survey [38] analyzes the barriers to the adoption of automated vehicles by using grey sets in their model and involving several academic experts and manufacturing representatives of the market. Hamadneh et al., [19] apply an integrated view with the involvement of four stakeholder groups, among others the users, to analyze the importance of some objectives and criteria of the AV industry. However, the potential risk of gaining untrustworthy responses from the evaluators of the survey is not considered, and fuzzy or grey sets are not applied to mitigate the uncertainty in scoring.

Thus, there is a lack of the classic demand side where the potential AV users' preferences are extensively examined in an integrated way. Therefore, a research gap for an integrated, multi-stakeholder decision-making-based survey using a grey model targeting the future perspectives of the AV industry can be identified. Table 1 below provides clearer evidence of the research gap identified in the preceding discussion by providing a concise overview of the studies summarized, along with other relevant research related to the AV industry conducted over the past five years. For each study, the table briefly presents the main research focus, the methodology employed, and the number of stakeholders involved.

2.2 Stakeholders involved in the AV sector

Listed criteria sets in the studies for the AV implementation are probably differently evaluated by the various stakeholders, it is suggested to provide an overview of the potential groups involved in the industry on both the supply and demand sides. Tengimoglu et al. [45] propose involving manufacturers, technology developers, and service providers from the supply side, while local and national authorities as well as academic institutions from the demand side. However, the users' perspectives are missing in their research.

Simultaneously, there are numerous surveys [18, 39] targeting the user side of AVs aiming to map the perceptions of the public. The users' aspects are essential; however, merely an integrated stakeholder analysis can reflect the perspectives of the industry as a whole. Moreover, the participants' motivation and interests in the transportation sector are often different [9, 20]; thus, they need to be synthesized to gain a sectoral consensus in the possible amelioration of transportation systems.

Consequently, in current paper, four stakeholder groups with different objectives are involved to evaluate the importance of various criteria related to the

Table 1 Overview of the literature related to the AV industry

Reference	Short topic	Method	# of Stakeholders
Dogan et al., [5]	Location selection of AV	Fuzzy AHP, TOPSIS	1
Raj et al., [38]	Barriers to the adoption of AV	Grey DEMATEL	1
Bakioglu and Atahan, [2]	Risks in self-driving vehicles	Pythagorean fuzzy AHP, TOPSIS, VIKOR	1
Jiang et al., [25]	City readiness for AV	AHP	6
Farrag et al., [11]	Adoption of AV	PROMETHEE, AHP	1
Jalwani and Choudhury, [24]	Barriers to the Adoption of AV	DEMATEL	1
Gamal et al., [13]	selection of an intelligent AV	MEREC, CoCoSo	1
Shahedi et al., [43]	Barriers to the adoption of AV	RBWM, IR-MABAC	1
Ullah et al., [46]	Barriers to Policies for Shared AV	F-AHP, F-TOPSIS	1
Ghoushchi et al., [15]	Efficiency of AVs	F-LMAW, FF-WASPAS	1
Verma and Rastogi, [48]	Perceived Transit Service Quality Attributes	Fuzzy-AHP	4
Duleba et al., [10]	Evaluate Perspectives of AV industry	FBW, AHP	4
Hoveidafard et al., [22]	Identification of Stations for AV	AHP, TOPSIS	1
Hamadneh et al., [19]	Stakeholder viewpoints analysis of AV	AHP	4
This paper	Robust criteria evaluation for AV by different stakeholders	Grey AHP	4

perspectives of the AV industry where some representatives of the manufacturers, users, legislators, and operators participate in the survey.

2.3 Criteria influencing the AV industry

AV can be considered and evaluated as any other transport mode. Travelers require reduced travel time [8, 49, 53] and mitigated transportation costs both from the supply and demand side [37, 49], while increased travel comfort [50] and travel safety [29] are crucial, as well. The environmental impact of AV belongs to the traditional evaluation criteria because the decreased total CO_2 emission is a fair expectation from this new form of mobility [54]. Spared parking time when using AVs can be another issue that affects the travelers' satisfaction [3]. Considering the enhanced data turnover connected to AV, data privacy [33] and cybersecurity [27] are essential criteria to be considered for all stakeholders.

As detailed in the previous sections, numerous studies have explored AV implementation criteria from different perspectives. Some of these studies have conducted separate evaluations for various stakeholder groups [4, 12, 19], while others were dealing with the intention to use AVs in developed and developing countries to better understand user perceptions [52]. However, apart from these few works, there remains a significant gap in the literature regarding the integrated and holistic assessment of these criteria across all stakeholders.

Among them, Hamadneh et al., [19] stands out as the most comprehensive study, systematically organizing AV-related criteria into main categories and sub-criteria considering the perspectives of multiple stakeholders. This structured approach makes it an essential reference for the current research. However, while their study offers a well-defined criteria set, it does not employ advanced decision-making methodologies capable of handling uncertainty, subjective judgments, and group decision-making complexities that are relevant and critical aspects in AV adoption analysis.

By incorporating grey AHP into the evaluation of these criteria, the present study extends the contributions of Hamadneh et al., [19] by addressing the inherent ambiguities, expert uncertainties, and overlapping decision factors that exist in real-world AV adoption scenarios. This approach enhances the precision and adaptability of prioritization, allowing for more nuanced insights into the relative importance of different criteria across diverse stakeholders.

The selected criteria, presented in Table 2 derived from the study of Hamadneh et al., [19], were deliberately chosen from well-established and widely adopted criterion sets in the AV literature to ensure both conceptual validity and methodological comparability with prior studies. By grounding the analysis in a recognized and previously validated set of criteria, this study enables meaningful cross-study comparisons and avoids the introduction of ad hoc or context-specific indicators that could limit generalizability. At the same time, employing this familiar benchmark allows the proposed grey AHP framework to be flexibly extended and rigorously tested, demonstrating its ability to capture uncertainty and stakeholder subjectivity more effectively than traditional approaches.

Building upon this foundation, the proposed framework is inherently designed to accommodate the inclusion of additional criteria or alternative decision-making methods when applied to different problem contexts and decision scenarios. Such modularity enables the model to be flexibly adapted without compromising its structural integrity or analytical rigor. As a result, policymakers and decision-makers are not constrained by a fixed or prescriptive evaluation structure; instead, they can derive context-specific model configurations tailored to their

Table 2 Stakeholders' objectives and criteria for AV implementation

St.	Obj.	Sy.	Criterion	Symbol	St.	Obj.	Sy.	Criterion	Symbol
USERS	Optimizing the travel time	**U1**	Reduction in the in-vehicle travel time	**U1C1**	**LEGISLATORS**	Decreasing the expenditures on infr. maintenance	**L1**	Reduction in damages caused by traffic accidents	**L1C1**
			Increased multitasking on board	**U1C2**				Increased efficiency of the existing road network	**L1C2**
			No parking time	**U1C3**		Minimizing the money spent on the health sector	**L2**	Increased vehicle and passenger safety	**L2C1**
			Acceptable waiting time	**U1C4**				Mobility for elderly people	**L2C2**
	Minimizing the travel cost	**U2**	Reduction in the fuel consumption	**U2C1**				Passive health monitoring	**L2C3**
			Reduction in the vehicle maintenance	**U2C2**		Protecting the environment	**L3**	Reduction in emissions	**L3C1**
			Reduction in the insurance	**U2C3**				Reduction in noise	**L3C2**
	Increasing the perceived comfort when traveling	**U3**	Information and guidance	**U3C1**				Efficient use of land use	**L3C3**
			Availability of ICT tools on board	**U3C2**				Efficient use of fuel	**L3C4**
			Reliability of travel time	**U3C3**		Assuring interoperability across borders	**L4**	Harmonization of laws	**L4C1**
	Respecting user rights	**U4**	Data privacy	**U4C1**				Technical standards	**L4C2**
			Cybersecurity	**U4C2**		Defining responsibilities among the actors	**L5**	The accountability and liability of malfunction	**L5C1**
	Increasing the travel safety	**U5**	Reduction in vehicle accidents caused by the malfunction of PSAV	**U5C1**				The accountability and liability of accidents caused by other vehicles	**L5C2**
			Reduction in accidents caused by regular cars with PSAV	**U5C2**				Policies to prevent technology monopoly	**L5C3**
	Ease of use	**U6**	No driving license	**U6C1**		Increasing social welfare	**L6**	Creation of new career opportunities	**L6C1**
			Accessibility	**U6C2**				Fairness and transparency	**L6C2**
OPERATORS	Increasing the revenues	**O1**	Optimized supply	**O1C1**		Ensuring user data privacy and system security	**L7**	Data privacy	**L7C1**
			Efficient use of the existing infrastructure	**O1C2**				Data ownership	**L7C2**

Table 2 (continued)

St.	Obj.	Sy.	Criterion	Symbol	St.	Obj.	Sy.	Criterion	Symbol
			Decrease in the number of accidents	**O1C3**				Cybersecurity	**L7C3**
	Multi-modal integration	**O2**	Connectivity with other modes	**O2C1**		Increasing the GDP	**L8**	Creation of new career opportunities	**L8C1**
			Increased accessibility	**O2C2**				Increased accessibility	**L8C2**
			Increased mobility	**O2C3**				Increased mobility	**L8C3**
	Increasing the efficiency of the TS	**O3**	Clear regulatory rules	**O3C1**				Land use development	**L8C4**
			Demand management	**O3C2**	**MANUFACTURERS**				
MANUFACTURERS	Providing user benefits	**M1**	Optimized travel time	**M1C1**		Maximizing the revenues	**M3**	Innovation and development	**M3C1**
			Minimized travel cost	**M1C2**				Increased reliability of the vehicles	**M3C2**
			Increased perceived comfort when traveling	**M1C3**				Sufficient supply	**M3C3**
			Ease of use	**M1C4**				Increased usage of PSAV	**M3C4**
	Increasing the trust of users	**M2**	Increase in safety	**M2C1**	**St. : Stakeholder** **Obj. : Objective** **Sy. : Symbol**				
			Data privacy	**M2C2**					
			Cybersecurity	**M2C3**					

particular policy objectives, regulatory environments, or stakeholder priorities. This adaptability significantly enhances the practical applicability of the framework, allowing it to function as a transferable and customizable decision-support tool across diverse AV-related policy and planning problems.

3 Methodology

In this section, the methodological foundations of the proposed evaluation approach, alongside the essential characteristics of the decision problem, are presented in a comprehensive manner. The first subsection outlines the identification, roles, and influence levels of all relevant stakeholder groups, thereby establishing the contextual environment in which the decision problem emerges. The second subsection provides a detailed articulation of the core decision challenge, including its operational boundaries, underlying assumptions, and the practical implications motivating the need for a structured assessment framework. The third subsection elaborates on the hierarchical organization of the decision objectives and the corresponding evaluation criteria used to guide the analysis. This part also discusses the theoretical rationale for criterion selection and their expected interactions within the decision-making environment. Finally, the fourth subsection presents an in-depth description of the methodological procedure, including the mathematical formulations, computational steps, and the grey-system extensions integrated into the traditional AHP structure to address uncertainty and incomplete information.

3.1 Stakeholder analysis

Various techniques exist to jointly involve the groups in the MCDM process. Each stakeholder has a weight in the decision-making process where their benefits, losses, opportunities, and risks are evaluated [25]. Multi-actor MCDM methods generally evaluate each stakeholder's role taking various criteria into account [23]. The evaluation process is almost the same with the classic MCDM process with two extra steps, i.e., determining the stakeholders and the stakeholders' weights.

The stakeholders are determined and examined through the knowledge presented in the literature review, where manufacturers, operators, legislators, and users are included in this research. Moreover, the stakeholders are weighted to reflect their importance in the decision-making process, so that the maximum utility is achieved from the process.

3.2 Problem definition

The aim of this study is to analyze different stakeholders' perspectives while adopting AVs since the adoption process is going to have a strong impact on everyday life [21]. However, the stakeholders' acceptability of AVs can be varied depending on the expected benefits. Therefore, several objectives and criteria are taken into consideration according to the stakeholders' expectations.

3.3 Objectives and criteria

The objectives and criteria for the evaluation are determined based on the literature review and expert opinions. The details of the chosen objectives and criteria of the stakeholders are given in Table 2. The table demonstrates the hierarchical structure of the AV acceptance by different stakeholders. The grey AHP calculations are realized according to this hierarchical structure where each stakeholder makes pairwise comparisons (PCs) for their own criteria sets. After filtering out the invalid or unusable entries, the total number of PC sets conducted across the four stakeholder groups (users, legislators, operators, and manufacturers) amounts to 30, 6, 8, and 6, respectively. The stakeholders use the linguistic scales demonstrated in Table 3 while doing the PCs. During the calculation process, the stakeholders are weighted according to their importance, preference, and needs. The details of weighting the stakeholders' evaluation while aggregating their PC matrices are provided in the following sub-section.

3.4 The proposed grey AHP method

AHP [41], one of the most widely accepted and extensively applied MCDM methods, is typically employed due to its ability to incorporate PCs among different criteria or alternatives. Despite its widespread use, the classical AHP framework relies on crisp numerical judgments, which may not adequately capture the nuances, uncertainties, and inherent subjectivity embedded in human evaluators' assessments, particularly in group decision-making contexts. The reliance on precise numerical inputs and traditional mathematical operations limits the capacity of classical AHP to model the variability and ambiguity present in expert opinions [14].

Table 3 Linguistic scales and their grey number representations for the grey AHP

Linguistic scale	Crisp value	Grey number
Extremely Low Important (ELI)	1/9	[0.111,0.125]
Very Low Important (VLI)	1/7	[0.125,0.167]
Low Important (LI)	1/5	[1.167,0.250]
Slightly Less Important (SSI)	1/3	[0.250,0.500]
Equally Important (EI)	1	[1,2]
Slightly More Important (SI)	3	[2,4]
Slightly High Importance (SHI)	5	[4,6]
Very High Importance (VHI)	7	[6,8]
Extremely High Importance (EHI)	9	[8,9]

To address the limitations and to more accurately reflect the diversity of individual judgments, the current study adopts the grey AHP approach [36]. Grey AHP extends the classical AHP by integrating grey system theory, enabling the representation of evaluators' opinions through interval-based grey numbers rather than deterministic values. This enhancement allows for a more realistic and flexible modeling of uncertainty, thereby improving the robustness and reliability of the overall decision-making process.

Within this research framework, grey AHP is utilized to evaluate and rank the criteria associated with AV implementation from the perspectives of diverse stakeholder groups. The methodological flowchart outlining the proposed grey AHP-based evaluation procedure, including the steps for constructing grey pairwise comparison matrices, deriving grey weights, and synthesizing the final rankings, is presented in Fig. 1. This structured process provides a systematic foundation for capturing stakeholder variability while ensuring methodological rigor in the assessment and prioritization of criteria.

A step-by-step calculation procedure of grey AHP is provided below for the evaluation of AVs.

Step 1 Determining the problem In this step the problem, the objectives, the criteria, the sub-criteria, and the alternatives are defined and scales are determined for the calculations. Additionally, the hierarchical structure of the problem is constructed in this step, too.

Step 2 Determining the scales and obtaining the PCs For the evaluation of AVs, both PCs and grey scale versions obtained from these PCs, are employed at different stages of the analysis to capture the complexity and uncertainty inherent in expert judgments. In this step, the PCs corresponding to the predefined objectives and criteria, as presented in Table 2, are conducted by utilizing the numerical scales outlined in Table 3. These scales enable evaluators to express the relative importance of each criterion in a structured and consistent manner. Subsequently, these evaluations are converted into their corresponding grey numbers, ensuring that the uncertainty and variability in expert judgments are formally represented within the model. Once transformed, the grey-valued data are incorporated into the subsequent analytical procedures, allowing the next steps of the methodology to operate on interval-based grey representations rather than deterministic values. This conversion process enhances the analytical rigor of the study by enabling a more comprehensive treatment of ambiguity and supporting more robust decision outcomes.

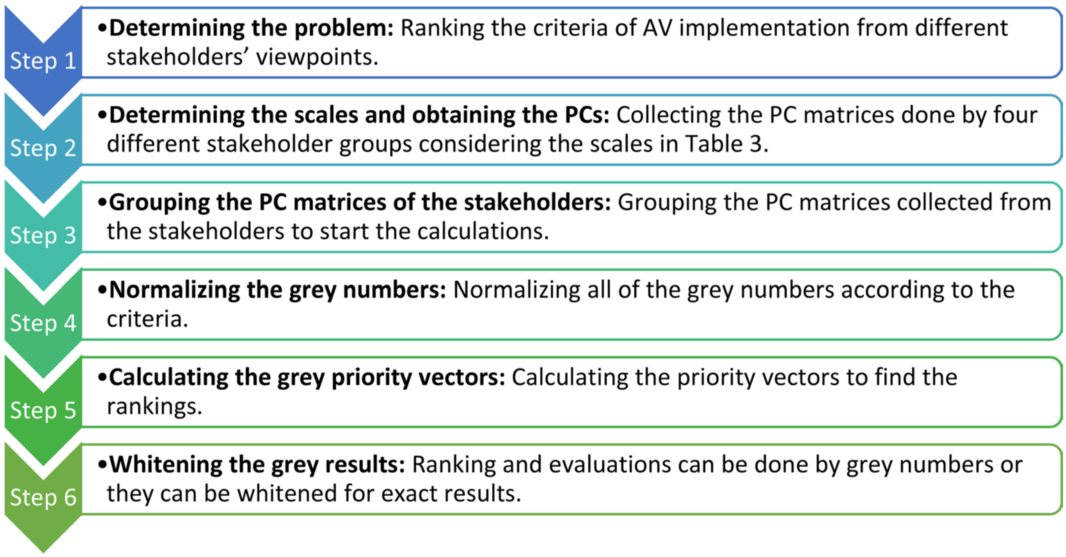

Fig. 1 Flowchart of the methodology for ranking the criteria of the AV implementation

Step 3 Grouping the PC matrices of the stakeholders $\otimes A^d$ in Eq. (1) is the PC matrix of a decision-maker $d \in D$, and $\otimes A$ is the aggregated PC matrix of the evaluators. Each element of the matrix, expressed as $\otimes a_{ij}^d = \left[\underline{a}_{ij}^d, \overline{a_{ij}^d}\right]$, refers to the grey-valued pairwise comparison between criteria *i* and *j*, capturing the lower and upper bounds of the evaluator's judgment interval. This representation enables the model to incorporate uncertainty and variability inherent in human decision-making processes.

$$\otimes A^d = \begin{bmatrix} \otimes a_{11}^d & \otimes a_{12}^d & \cdots & \otimes a_{1n}^d \\ \otimes a_{21}^d & \otimes a_{22}^d & \cdots & \otimes a_{2n}^d \\ \vdots & \vdots & \otimes a_{ij}^d & \vdots \\ \otimes a_{n1}^d & \otimes a_{n2}^d & \cdots & \otimes a_{nn}^d \end{bmatrix} \tag{1}$$

$$\otimes a_{ij}^d = \frac{1}{\otimes a_{ji}^d} = \left[\frac{1}{\overline{a_{ji}^d}}, \frac{1}{\underline{a}_{ji}^d}\right] \tag{2}$$

For the aggregation of individual PC matrices done by the evaluators into a collective assessment, the weighted geometric mean method [6, 28], given in Eq. (3), is applied. This approach is widely recognized for its suitability in combining ratio-scale judgments and for preserving the multiplicative structure of pairwise comparisons. In contrast, for other evaluation matrices constructed using grey numbers derived from percentage-based assessments, the weighted arithmetic mean is adopted. The use of the arithmetic mean in these cases is necessitated by the presence of zero values within the data, which would otherwise render the geometric aggregation method mathematically inappropriate. Together, these aggregation strategies ensure consistency while adequately addressing the characteristics of the different types of evaluation inputs used throughout the analysis.

$$\otimes a_{ij} = \sqrt[W_D]{\prod_{d=1}^{D} \left(\otimes a_{ij}^d\right)^{\lambda_d}} \epsilon \otimes A \tag{3}$$

$$W_D = \sum_{d \epsilon D} \lambda_d \tag{4}$$

Step 4 Normalizing the grey numbers The normalization of the grey numbers corresponding to each criterion is performed by applying Eqs. (5–6), both of which are adapted from the methodological formulations proposed by Wu and Lee [51]. Equation (5) is for the lower bounds of the grey numbers and Eq. (6) is for the upper bounds of the grey numbers. These normalization procedures are essential for transforming the interval-based grey evaluations into a comparable scale among all criteria set, thereby ensuring consistency across criteria that may originally possess differing ranges or measurement characteristics. By standardizing the lower and upper bounds of each grey number, the process facilitates a coherent integration of all criteria into the subsequent steps of the grey AHP analysis. This step not only preserves the intrinsic uncertainty represented by the grey intervals but also enhances analytical rigor by enabling meaningful synthesis and comparison across the full set of evaluation metrics.

$$\otimes\underline{a_{ij}} = \frac{\otimes\underline{a_{ij}} - \min\limits_{j} \otimes \underline{a_{ij}}}{\max\limits_{j} \otimes \overline{a_{ij}} - \min\limits_{j} \otimes \underline{a_{ij}}} \tag{5}$$

$$\otimes\overline{a_{ij}} = \frac{\otimes\overline{a_{ij}} - \min\limits_{j} \otimes \underline{a_{ij}}}{\max\limits_{j} \otimes \overline{a_{ij}} - \min\limits_{j} \otimes \underline{a_{ij}}} \tag{6}$$

Step 5 Calculating the grey priority vectors This step follows a procedure analogous to that of the traditional AHP framework. Specifically, the priority value of each criterion is obtained by calculating the average of the corresponding row in the grey pairwise comparison matrix. This computation yields the components of the priority vector, denoted as $\otimes PV = [\otimes pv_i]_{n\times 1}$, where each $\otimes pv_i$ represents the grey priority weight associated with criterion i.

The mathematical formulation used for deriving these priorities is presented in Eq. (7), in which C refers to the total number of criteria. Through this averaging procedure, the method synthesizes the interval-based comparative judgments into a coherent set of grey priority values. These values reflect the relative importance of the criteria while preserving the uncertainty captured by the grey numbers, thereby ensuring consistency with the underlying principles of grey system theory and the overall structure of the grey AHP approach.

$$\otimes pv_i = \frac{\sum_{j=1}^{C} \otimes a_{ij}}{C} \tag{7}$$

Step 6 Whitening the grey results The results of the analytical procedure may initially be expressed in the form of grey numbers, which effectively capture uncertainty and the range of possible judgments. Although such interval-based representations are valuable for reflecting ambiguity in expert evaluations, certain decision-making contexts require more definitive, crisp numerical results to facilitate clear comparisons and actionable interpretations. For this reason, a whitening process is applied to convert the grey priority vector into a crisp priority vector.

Repeating the normalization steps for the grey priority vector, it is whitened by applying Eqs. (8–9), as proposed by Wu and Lee [51]. Through this whitening procedure, the interval-valued grey priorities are systematically mapped to single-valued crisp weights, resulting in the priority vector $P = [p_i]_{n\times 1}$. This vector provides precise numerical importance values for each criterion, enabling a more straightforward interpretation of the results and supporting subsequent steps of decision analysis that rely on deterministic inputs.

Table 4 The stakeholders' priority weight results

Stakeholder	Grey results	Crisp results	Ranking
Users	[0.469,1.000]	0.5702	1
Legislators	[0.277,0.679]	0.3445	2
Operators	[0.013,0.100]	0.0486	3
Manufacturers	[0.000,0.058]	0.0367	4

Table 5 A PC matrix example for optimizing the travel time objective

Criterion		C1	C2	C3	C4
Reducing in-vehicle travel time	**C1**	EI	VLI	LI	SSI
Increased multitasking on board	**C2**	VHI	EI	SI	SHI
No parking time	**C3**	SHI	SSI	EI	SI
Acceptable waiting time	**C4**	SI	LI	SSI	EI

$$Y_i = \frac{\otimes\underline{a_i}\left(1 - \otimes\underline{a_i}\right) + \otimes\overline{a_i} \otimes \overline{a_i}}{1 - \otimes\underline{a_i} + \otimes\overline{a_i}} \tag{8}$$

$$p_i = \min_i \otimes \underline{a_i} + Y_i \left(\max_i \otimes \overline{a_i} - \min_i \otimes \underline{a_i} \right) \tag{9}$$

4 Results

4.1 The stakeholders' ranking

In this section, the evaluation of the different stakeholders' perspectives while adopting AVs is realized by applying the grey AHP method. Considering all stakeholders, in total 50 experts of transportation systems and technology evaluated the survey. The evaluators represent research institutions, governmental institutions, vehicle manufacturers, operators, and users. For AHP-type surveys, smaller samples can be trustworthy, which means that a pattern with 20 respondents could be a sufficient number to evaluate MCDM problems [1]. According to the evaluators' responses about the priority among the stakeholders, the users have the highest weight in the decision-making process with 57%, the legislators have the second highest weight with 34%, while the operators have 5%, and the manufacturers have 4%. These results show that the users and the legislators have a key role in adopting the new transport mode (Table 4).

4.2 Analysis of the users

According to Table 2, the "Optimizing the travel time" objective has the highest number of criteria for the users with four criteria. As an example, the PC matrix of the evaluators regarding the travel time is shown in Table 5, representing a sample matrix constructed by a single evaluator and is provided solely for illustrative purposes. Given the dimensionality of the PC matrices and a significant number of evaluations—reaching into the hundreds—it is neither practical nor feasible to present all individual PC matrices within this manuscript. Therefore, in the subsequent sections, individual PC matrices are not reported separately; instead, the aggregated comparison results derived from these matrices are presented and used as the basis for analysis and interpretation of the findings.

After obtaining the PCs from the evaluators, like the PC of one evaluator in Table 5, the PC matrices of all evaluators are aggregated, and the normalized PC matrix with grey numbers is calculated for optimizing the travel time objective as demonstrated in Table 6.

After the PC matrices are collected from the users and the calculations are completed, the results presented in Table 7; Fig. 2 are obtained. For example, the results for the "Optimizing the travel time" objective are calculated by using the normalized PC matrix provided in Table 6. The columns for the rankings are built from highest to lowest, from the most important to the least important. The third column is for ranking the objectives, the seventh column is for ranking the criteria in each objective, and the last column is for ranking all criteria together.

According to the results, "Optimizing the travel time" is the most important objective, and "Increasing the travel safety" is the second most crucial objective, while "Increasing the perceived comfort when traveling", "Minimizing the travel cost", "Respecting user rights" and "Ease of use" are less important objectives for the users. This priority indicates that the users are interested in quick and safe transportation when using AVs and pay less attention to other issues. Since the "Minimizing the travel cost" objective receives the fourth position in the ranking, the results show that the users' willingness to pay can be higher compared to other transport modes. Additionally, it is noted that the technical issues connected to handling the vehicle are not in the focus of this group possibly due to their technological readiness (using smart devices already). Some user rights might be sacrificed to access fast and safe mobility according to the users' scoring.

When evaluating the criteria, the "Reducing in-vehicle travel time" criterion is the most important with a weight of 0.8072 for the "Optimizing the travel time" objective, and it is the most crucial criterion among all the criteria for the users. The "Reduction in the fuel consumption" criterion is the most important with the weight of 0.9266

Table 6 Aggregated normalized PC matrix with grey numbers

Criterion		C1	C2	C3	C4
Reducing in-vehicle travel time	**C1**	[0.434, 0.542]	[1.407, 2.452]	[0.924, 1.843]	[0.832, 1.654]
Increased multitasking on board	**C2**	[0.025, 0.050]	[0.115, 0.164]	[0.070, 0.173]	[0.079, 0.188]
No parking time	**C3**	[0.040, 0.099]	[0.130, 0.346]	[0.137, 0.210]	[0.075, 0.208]
Acceptable waiting time	**C4**	[0.053, 0.125]	[0.141, 0.351]	[0.163, 0.440]	[0.161, 0.240]

for the "Minimizing the travel cost" objective, and it is the second most crucial criterion among all criteria for the users. This is a very strong indication that the users have a concern for high fuel price and consider AVs as a possible solution for reducing fuel consumption either by substituting gasoline with electricity (i.e., AVs are often connected with electric vehicles) [40] or by optimizing the routes and driving style. All other cost issues have insignificant importance with overall low positions in the total set of criteria. The "Reliability of travel time" criterion with a weight of 0.7690 is the most important for the "Increasing the perceived comfort when traveling" objective. For the "Respecting user rights" objective, the "Data privacy" criterion is the most crucial with the weight of 0.6633. Moreover, with the weight of 0.7711, the "Reduction in vehicle accidents caused by the malfunction of PSAV" criterion is the most important for the "Increasing the travel safety" objective. Additionally, it is the third most crucial criterion among all the criteria for users. Finally, the "Accessibility" criterion is the most important with the weight of 0.8718 for the "Ease of use" objective.

When checking the results in detail, the sensitivity among some of the objectives starts from the third digit after the dot. Thus, it can be said that the ranking of the first and second most important objectives can be changed according to the different situations or evaluators. Especially, if the grey numbers are considered, it is worth noting that there is no significant difference between the results of the two objectives.

Furthermore, Table 7 demonstrates the sophistication characteristic of the grey methodology compared to the traditional AHP. In the two final rankings, the maximum deviation is three positions, which indicates a precise calculation considering the evaluators' insecure scoring, which is more relevant in the user group. There is merely one exception, the "Reduction in the in-vehicle travel time" objective gains the first position in the grey AHP while it is ranked merely eighth in the traditional AHP. It is worth noting that this objective has the highest score in its branch (U1) in both cases, the reason for the difference is the smaller weight score of the total branch. The key role of the grey AHP calculation is emphasized because it sheds light on the users' time consideration. However, the traditional AHP is not capable of considering this perspective, merely safety and accessibility are highly ranked in that case.

The results illustrated in Fig. 2 are derived from the criteria listed under the objectives in the sixth column of Table 7. By jointly evaluating the rankings of these criteria sets, the analysis provides an integrated assessment that enables clear visual comparison of criteria importance across objectives, thereby enhancing the interpretability of inter-objective priority relationships.

Table 7 The weights of the objectives and criteria with their rankings for the users

Obj.	Grey AHP		Traditional AHP		Crit.	Grey AHP				Traditional AHP		
	Weight	R.	Weight	R.		Grey Weight	Crisp Weight	R.	Final Rank.	Weight	R.	F. R.
U1	0.1853	1	0.1813	2	U1C1	[0.533,1.000]	0.8072	1	1	0.4123	1	8
					U1C2	[0.000,0.046]	0.0441	4	15	0.1666	3	15
					U1C3	[0.015,0.092]	0.0616	3	13	0.1561	4	16
					U1C4	[0.037,0.140]	0.0871	2	11	0.2649	2	9
U2	0.1586	4	0.1626	3	U2C1	[0.579,1.000]	0.9266	1	2	0.5929	1	3
					U2C2	[0.028,0.078]	0.0529	2	14	0.2138	2	13
					U2C3	[0.000,0.017]	0.0206	3	16	0.1932	3	14
U3	0.1609	3	0.1580	5	U3C1	[0.032,0.174]	0.1338	2	9	0.2472	2	11
					U3C2	[0.000,0.104]	0.0973	3	12	0.2379	3	12
					U3C3	[0.477,1.000]	0.7690	1	5	0.5149	1	5
U4	0.1564	5	0.1593	4	U4C1	[0.407,1.000]	0.6633	1	6	0.4885	2	7
					U4C2	[0.000,0.356]	0.3367	2	7	0.5115	1	4
U5	0.1827	2	0.1864	1	U5C1	[0.540,1.000]	0.7711	1	3	0.5815	1	1
					U5C2	[0.000,0.173]	0.2289	2	8	0.4185	2	6
U6	0.1560	6	0.1523	6	U6C1	[0.000,0.092]	0.1282	2	10	0.2992	2	10
					U6C2	[0.547,1.000]	0.8718	1	4	0.7008	1	2

4.3 Analysis of the legislators

After the PC matrices from the legislators are collected and the calculations are conducted, the results demonstrated in Tables 8 and Fig. 3 are obtained. According to the results, “Increasing the GDP” is the most important, and “Protecting the environment” is the second most important objective, while “Decreasing the expenditures on infrastructure maintenance”, “Minimizing the money spent on the health sector”, “Increasing social welfare”, “Defining responsibilities among the actors”, “Ensuring users’ data privacy and system security”, and “Assuring interoperability across borders” are less important objectives for the legislators. The priority shows that this decision-maker group connects the expected improved mobility with the boosted economy directly and sees the advantages of AVs. Environmental aspects are related to different fuel types or optimized driving, which reflects the users’ aspects, as well. Interestingly, the criteria related to these two objectives could not reach high positions (e.g., for “Increasing the GDP” merely 7th or worse, and for ”Protecting the environment” 5th or worse), which means that they are appreciated when considering the big picture but owing to the specific issues, other advantages gain higher attention.

When evaluating the criteria, the “Reduction in damages caused by traffic accidents” criterion is the most important with the weight of 0.7753 for the “Decreasing the expenditures on infrastructure maintenance” objective. Among all criteria for the legislators, this objective is the second most important. Similarly to the case of the users, safety is considered as a main issue. Another evidence is that with the weight of 0.7890, the “Increased vehicle and passenger safety” criterion is the most important for the “Minimizing the money spent on the health sector” objective, and it is also important when considering all criteria for the legislators. Even though elderly people’s mobility gains a very low place in the ranking, this is due to the dominance of the safety issue since they are evaluated in the same branch of the structure. It is emphasized that because of their reduced ability to drive and move, this age group could be a target group of AV transportation, especially in case of L4 and L5 levels. However, safety issues are so strong that in recent situations, they have primacy over the age-segmented opportunities. The “Reduction in emissions” criterion is the most important with the weight of 0.6609 for the “Protecting the environment” objective. For “Assuring interoperability across borders” objective, the “Harmonization of laws” criterion is the most important with the weight of 0.7859, and it is the third most crucial criterion among all criteria for the legislators.

When the grey AHP and traditional AHP rankings are compared, it can be stated that the positions are similar with a slightly more deviation than in case of the user

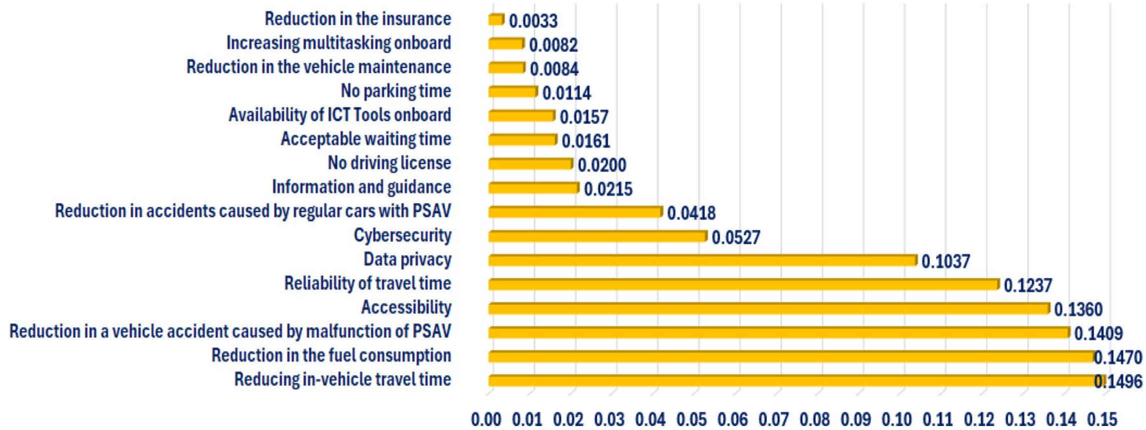

Fig. 2 The rankings of the final weights of the criteria for the users

group. The "Creation of new carrier opportunities" criterion has the top ranking in the conventional methodology, which is peculiar if the three other stakeholder groups' preferences are considered. The grey AHP prioritizes the safety issue, which is much more coherent with all other evaluator groups. Thus, it can be stated that utilizing grey sets helps in creating a more integrated and more consensual overall priority ranking of the objectives and criteria of AV thus reflecting all stakeholders' whole view on the industry.

Similar to the results reported for the user group, the results presented in Fig. 3 are generated based on the criteria listed under the objectives in the sixth column of Table 8. This visualization enables the simultaneous evaluation of all 23 criteria distributed across different objectives in Table 8, allowing their relative importance to be observed more clearly in a unified graphical representation. Such visualizations are particularly valuable in decision-making problems involving large and complex criterion sets, as they significantly enhance interpretability and facilitate a more intuitive comparison of criterion priorities.

4.4 Analysis of the operators

After the PC matrices from the operators are collected and the calculations are conducted, the results shown in Table 9; Fig. 4 are obtained. According to the outcomes, "Increasing the revenues" is the most important objective, while "Multimodal integration" and "Increasing the efficiency of the transportation system" are less crucial objectives for the operators. This is an expected result since the representatives of this group are dedicated to generating profit from the operations. However, the criteria ranking shows some interesting preferences.

When evaluating the criteria, the "Optimized supply" criterion is the most important with the weight of 0.6372 for the "Increasing the revenues" objective. Additionally, it is the most important among all criteria for the operators. Within this group of criteria, the other two competitors related to less accidents and better infrastructure utilization performed high. This phenomenon can be explained by the operators' awareness of the optimization possibilities of automated traffic and the profitability, which can be reached through that. For the "Multimodal integration" objective, the "Connectivity with other modes" criterion is the most important with the weight of 0.6057. This criterion is the second most important among all criteria for the operators. This is a very strong position indicating that operators consider transportation networks. Finally, the "Clear regulatory rules" criterion is the most important for the "Increasing the efficiency of the transportation system" objective.

Owing to the comparison of grey and conventional AHP models, in this group, the robustness is even more detected than in case of the users. The maximum deviation in positions is merely one place, and most of the rankings are identical. Thus, for the legislator group, the grey sets contribute to the more precise ranking by considering the uncertainty of the evaluator scoring.

The visualization presented in Fig. 4 is constructed based on the results of the eight criteria listed in the sixth column of Table 9, where the comparisons discussed thus far can be observed more clearly. Given that the total number of criteria is relatively small, the results can also be readily and accurately interpreted directly from the table without the need for graphical representation. Figure 4 is provided to maintain consistency with the preceding analyses and to offer an intuitive visual confirmation of the comparative relationships among the criteria.

4.5 Analysis of the manufacturers

After the PC matrices from the operators are collected and the calculations are completed, the outcomes presented in Table 10; Fig. 5 are obtained. According to the results, "Increasing the users' trust" is the most important

Table 8 The weights of the objectives and the criteria with their rankings for the legislators

Obj.	Grey AHP		Traditional AHP		Crit.	Grey AHP				Traditional AHP		
	Weight	R.	Weight	R.		Grey Weight	Crisp Weight	R.	Final Ranking	Weight	R.	F.R.
L1	0.1240	3	0.1238	4	L1C1	[0.606,1.000]	0.7753	1	2	0.5319	1	5
					L1C2	[0.000,0.148]	0.2347	2	14	0.4681	2	8
L2	0.1228	4	0.1243	3	L2C1	[0.621,1.000]	0.7890	1	1	0.5254	1	6
					L2C2	[0.135,0.284]	0.1778	2	16	0.2761	2	15
					L2C3	[0.000,0.021]	0.0331	3	22	0.1985	3	19
L3	0.1339	2	0.1337	2	L3C1	[0.410,1.000]	0.6609	1	5	0.4504	1	7
					L3C2	[0.148,0.420]	0.2186	2	13	0.2475	2	16
					L3C3	[0.062,0.199]	0.0945	3	18	0.2039	3	18
					L3C4	[0.000,0.039]	0.0261	4	23	0.0982	4	23
L4	0.1166	8	0.1164	8	L4C1	[0.531,1.000]	0.7859	1	3	0.6667	1	4
					L4C2	[0.000,0.165]	0.2141	2	15	0.3333	2	14
L5	0.1178	6	0.1176	6	L5C1	[0.420,1.000]	0.6173	1	6	0.4067	1	10
					L5C2	[0.147,0.467]	0.2717	2	12	0.3893	2	12
					L5C3	[0.000,0.134]	0.1110	3	17	0.2040	3	20
L6	0.1210	5	0.1466	1	L6C1	[0.432,1.000]	0.7346	1	4	0.6426	1	1
					L6C2	[0.000,0.260]	0.2654	2	11	0.3574	2	9
L7	0.1171	7	0.1208	5	L7C1	[0.378,0.937]	0.4615	2	10	0.6925	2	3
					L7C2	[0.000,0.084]	0.0527	3	21	0.3879	3	11
					L7C3	[0.370,1.000]	0.4859	1	9	0.7743	1	2
L8	0.1468	1	0.1169	7	L8C1	[0.357,0.934]	0.4046	2	8	0.3471	1	13
					L8C2	[0.425,1.000]	0.4503	1	7	0.2826	2	17
					L8C3	[0.016,0.199]	0.0785	3	19	0.2021	3	21
					L8C4	[0.000,0.165]	0.0667	4	20	0.1682	4	22

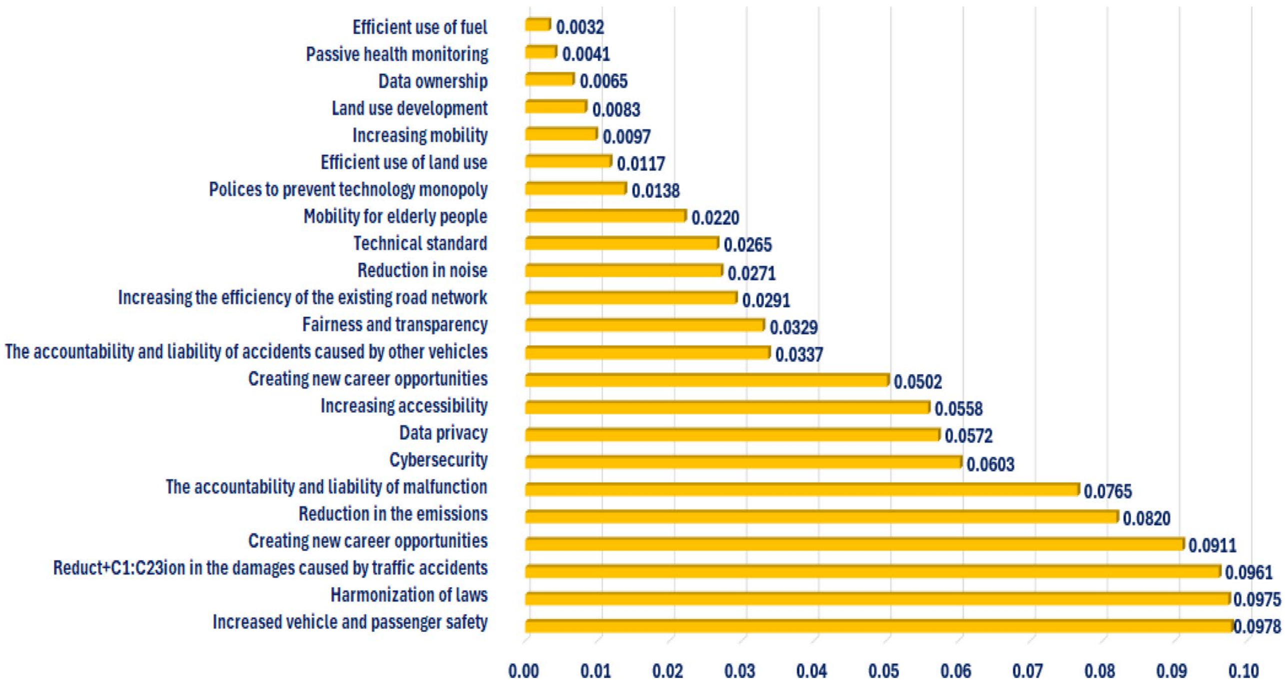

Fig. 3 The rankings of the final weights of the criteria for the legislators

objective, while "Maximizing the revenues" and "Providing user benefits" are less crucial objectives for the manufacturers. The results show that the representatives of this group are clearly aware of the public needs for the safety of autonomous driving, especially in case of the L4 and L5 levels. It is worth noting that the scores of trust in safety are even higher than the revenue maximization, which means that this group considers trust as a precondition of increasing the revenues from sales.

In the criteria ranking, other evidence for this statement can be seen. The "Minimized travel cost" criterion is the most important with a weight of 0.7009 for the "Providing user benefits" objective. Moreover, it is the third most crucial criterion among all criteria for the manufacturers. For the "Increasing the users' trust" objective, the "Increase in safety" criterion with a weight of 0.9481 is the most important, and it is the most important criterion among all criteria for the manufacturers. With the weight of 0.8433, the "Increased reliability of the vehicles" criterion is the most crucial for the "Maximizing the revenues" objective, and it is the second most important criterion when considering all criteria for the manufacturers.

It has to be highlighted that the easy usage is rather low ranked by the manufacturers, which might be unexpected without knowing that the users evaluate this criterion low, as well. This indicates a clear industrial image on the users' needs. The explanation could be the widespread smart device utilization as well as the application of artificial intelligence by several potential AV users and the proper sight of the manufacturing companies on this social phenomenon.

In case of the manufacturers, the robustness is visible. Merely two positions are the maximum deviation between the grey and traditional AHP models even if there are 11 criteria and not solely eight as in case of the legislator cluster. The first and second positions are the same. However, in the third place, "Cybersecurity" can be found in the AHP model, and the "Minimized travel cost" criterion is indicated in the grey AHP. The grey sets help reflect the user needs on reduced fuel consumption, which has already been clarified in that cluster, while the traditional AHP mitigates this need.

As clearly illustrated in Fig. 5, which is derived from the results of the eleven criteria reported in the sixth column of Table 10, the criterion "Increase in Safety emerges as overwhelmingly dominant from the manufacturers' perspective", with an importance weight of 71.02%. This value is markedly higher than those of the remaining criteria, indicating a substantial prioritization gap. The second-ranked criterion, "Increased Reliability of the Vehicles", follows with an importance weight of 11.71%; however, the difference in relative importance between these two criteria remains considerable.

The percentage weights presented in Fig. 5 are calculated by multiplying the objective-level weights obtained via the grey AHP method (reported in the second column of Table 10) with the corresponding local weights of the criteria under each objective (reported in the eighth column of Table 10). This aggregation procedure ensures

Table 9 The weights of the objectives and the criteria with their rankings for the operators

Obj.	Grey AHP		Traditional AHP		Crit.	Grey AHP				Traditional AHP		
	Weight	R.	Weight	R.		Grey Weight	Crisp Weight	R.	Final Ranking	Weight	R.	F. R.
O1	0.5589	1	0.4326	1	O1C1	[0.349,1.000]	0.6372	1	1	0.4423	1	1
					O1C2	[0.000,0.209]	0.1440	3	6	0.2310	3	7
					O1C3	[0.066,0.349]	0.2187	2	4	0.3267	2	3
O2	0.2345	2	0.3261	2	O2C1	[0.454,1.000]	0.6057	1	2	0.4496	1	2
					O2C2	[0.200,0.597]	0.3151	2	7	0.3323	2	6
					O2C3	[0.000,0.125]	0.0793	3	8	0.2180	3	8
O3	0.2066	3	0.2412	3	O3C1	[0.223,1.000]	0.6084	1	3	0.5052	1	4
					O3C2	[0.000,0.569]	0.3916	2	5	0.4948	2	5

that the visualized results accurately reflect both the hierarchical structure of the decision model and the uncertainty-aware weighting mechanism inherent in the grey AHP approach.

5 Discussion

5.1 Stakeholder analysis

Understanding the relative influence of different stakeholder groups is essential for the successful implementation of AVs. Each stakeholder plays a distinct role in shaping the adoption process, yet their priorities and decision-making power vary significantly. In this section, the overall ranking of stakeholders is analyzed, providing insights into the broader dynamics of AV adoption. This approach allows for a comprehensive evaluation of the macro-level stakeholder hierarchy that shapes individual perspectives within the AV ecosystem.

With the highest weight (0.5702), users emerge as the dominant stakeholder group in AV implementation. This outcome is expected, as the widespread adoption of AV technology is ultimately dependent on user acceptance, trust, and willingness to integrate these vehicles into daily life. Users' concerns about the different consequences and benefits of AV play a decisive role in shaping the regulatory and technological development of AVs.

Legislators rank second (0.3445), highlighting the significant role of government bodies and policymakers in shaping AV adoption. Regulatory frameworks influence the pace of technological integration by defining safety standards, liability regulations, data privacy policies, and infrastructure readiness. The considerably high weight of legislators suggests that despite technological advancements, legal and ethical considerations remain major challenges for AV adoption. Strict policies on road safety, accident accountability, and cybersecurity can facilitate the development of AV technology, depending on how effectively they address public and industry concerns.

Operators rank third with a relatively low weight of 0.0486. While these stakeholders are essential in defining business models for AV deployment, their influence appears limited compared to users and legislators. This could be because operators' decisions are largely dependent on regulatory approvals and public acceptance. Manufacturers, despite being the primary developers of AV technology, rank the lowest (0.0367). This result indicates that technological advancements alone are insufficient for AV adoption unless they align with user expectations and regulatory requirements. While manufacturers drive innovation, their ability to influence AV deployment is constrained by external factors, such as policy restrictions, public trust, and market demand. This finding suggests that successful AV implementation requires collaborative effort, where manufacturers work

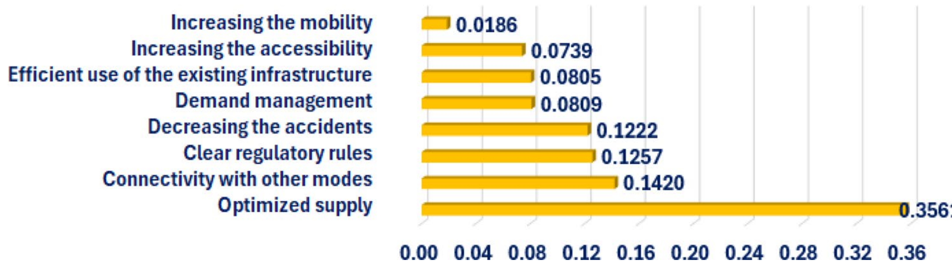

Fig. 4 The rankings of the final weights of the criteria for the operators

closely with regulators, users, and service operators to develop solutions that align with societal needs.

The ranking highlights the need for a user-centric approach to AV adoption, ensuring that technological advancements address public concerns and safety expectations. Legislators must also play a proactive role in creating balanced regulations that facilitate innovation while ensuring public safety. Additionally, collaborations between operators, manufacturers, and policymakers are essential for addressing practical deployment challenges.

5.2 Findings and recommendations

The findings provide a nuanced understanding of AV implementation by explicitly demonstrating how different stakeholder groups prioritize evaluation criteria in distinct ways, while also identifying those criteria that emerge as universally influential across stakeholder perspectives. Through the application of the grey AHP framework, instead of classical AHP, the analysis captures these variations without being overly constrained by subjective or individual judgment biases, thereby offering a more flexible and robust aggregation of stakeholder preferences under uncertainty. The results indicate that safety consistently ranks as the most influential criterion across all stakeholder groups, underscoring its central role in shaping user trust, regulatory acceptance, and overall societal readiness for AV deployment [35]. This convergence highlights safety as a non-negotiable foundation for AV adoption, irrespective of stakeholder role or interest.

At the same time, the prioritization of secondary criteria varies meaningfully across groups. From the user perspective, minimizing travel time and fuel consumption emerge as key determinants of perceived value, directly influencing adoption willingness and affordability-related policy considerations. In contrast, revenue-oriented stakeholders place greater emphasis on vehicle reliability, reflecting the critical role of consistent operational performance in sustaining profitability and long-term market viability. By accommodating such heterogeneous priorities, the grey AHP-based model enables a more realistic representation of stakeholder-driven decision dynamics. Overall, these results demonstrate that the proposed methodology not only identifies shared strategic priorities but also effectively differentiates stakeholder-specific concerns, thereby supporting the development of balanced, transparent, and policy-relevant decision-support outcomes for AV implementation.

Based on the findings, several recommendations can be made for stakeholders of the industry:

- Users should be educated to mitigate fears and prejudices surrounding driverless vehicles, which would enhance public acceptance.
- Legislators should focus on law harmonization concerning accidents and responsibility in AV traffic, while working to ensure that regulations are clear and fair.
- Operators are encouraged to optimize the running of AVs with special attention to connectivity with other transport modes, ensuring a seamless transportation network.
- Manufacturers should prioritize safety and reliability in the development of AVs to foster consumer confidence.

Finally, the research questions raised in the Introduction section can be responded to as follows.

R1: The presented grey AHP model can be considered as a superior method compared to the traditional AHP because of taking into account the ambiguity of responses. Even though the local rankings of the criteria are similar, due to the impact of slight differences on the final preference scores, the global ranking is substantially different. The most important alteration is within the Users group, for the criterion of 'Reducing in-vehicle travel time' and its exceptional importance, which could not be indicated by the original method.

R2: The outcome of the stakeholder-wise evaluation has become more understandable by the proposed method for all four groups. It is interesting that Manufacturers do not consider the ease-of-use issue significant, but the prioritization of safety-related criteria completes the expectations.

R3: The recommendations can be found in the bullet-point part of this sub-section.

Table 10 The weights of the objectives and the criteria with their rankings for the manufacturers

Obj.	Grey AHP		Traditional AHP		Crit.	Grey AHP				Traditional AHP		
	Weight	R.	Weight	R.		Grey Weight	Crisp Weight	R.	Final Ranking	Weight	R.	F. R.
M1	0.1121	3	0.1915	3	M1C1	[0.105,0.266]	0.1360	3	7	0.1730	3	9
					M1C2	[0.494,1.000]	0.7009	1	3	0.4331	1	4
					M1C3	[0.115,0.268]	0.1431	2	6	0.2955	2	6
					M1C4	[0.000,0.027]	0.0200	4	10	0.0984	4	11
M2	0.7491	1	0.5181	1	M2C1	[0.575,1.000]	0.9481	1	1	0.6809	1	1
					M2C2	[0.007,0.037]	0.0299	2	4	0.1580	3	5
					M2C3	[0.000,0.020]	0.0220	3	5	0.1611	2	3
M3	0.1388	2	0.2904	2	M3C1	[0.072,0.201]	0.1029	2	8	0.1811	2	7
					M3C2	[0.560,1.000]	0.8433	1	2	0.5588	1	2
					M3C3	[0.028,0.084]	0.0422	3	9	0.1710	3	8
					M3C4	[0.000,0.012]	0.0115	4	11	0.0891	4	10

5.3 Limitations

Despite its contributions, this study has limitations, such as the potential specificity of its results to particular regions or markets, and the need for further refinement of the methodology by fostering stakeholder consensus. Even though the method and survey design can be directly applied to other fields, the results can be country- or market-specific. Thus, possible local characteristics should be considered when extending the results to other regions or markets. It is also proposed that adding more alternatives and performing additional surveys could improve the model results. The research emphasizes the importance of integrating stakeholder perspectives in AV planning, focusing on safety, reliability, affordability and addressing concerns like data privacy and cybersecurity to ensure successful AV adoption. The proposed grey AHP model can be adapted for various settings and integrated with AI to track evolving stakeholder priorities.

5.4 Future orientations

The outcome verifies that fostering higher levels of automation takes general and stakeholder-customized evaluation by transport planners. For stakeholder-specific preference factors the limitations of financial resources, time, and technological boundaries require prioritization from AV decision-makers, which could be supported by the results of the current paper.

Since the efficient (and sustainable) allocation of AV development resources is only possible if all relevant stakeholder groups confirm the development scenario, in the future the consensus creation will be a crucial element. However, considering the nature of the participant sides, instead of the traditional, negotiation-based approach, a more objective and unbiased methodology will be necessary to reach an acceptable development consensus for AV adoption. Overall, a balanced approach, considering both technological and social factors, is key to the long-term success of AVs, with future research exploring consensus-building and societal challenges for sustainable implementation.

6 Conclusion

This study offers a profound understanding of the varying priorities and concerns that influence the successful adoption and deployment of AVs, where it is critical to address the expectations and requirements of relevant stakeholders, such as users, legislators, operators, and manufacturers. Current research uses the grey AHP method to systematically evaluate and rank the criteria that the different stakeholders consider important in the context of AV implementation. The grey AHP model used in this study provides a balanced view on multiple criteria that must be considered during the implementation

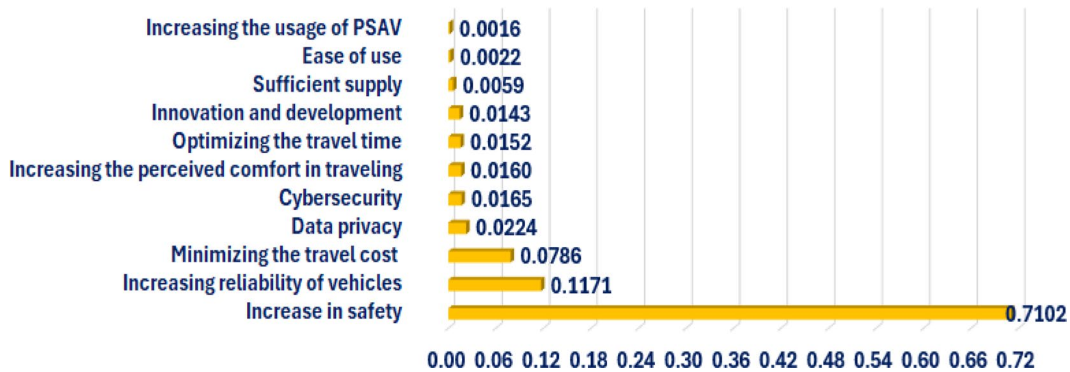

Fig. 5 The rankings of the final weights of the criteria for the manufacturers

of AVs. By incorporating various stakeholders' perspectives, the research ensures that the priorities and trade-offs are adequately understood, enabling more informed decision-making. The conclusion emphasizes that while technological advancements are essential, the successful deployment of AVs depends on a holistic approach that considers technological, economic, and social factors. The insights suggest that future policies should focus on enhancing safety, ensuring affordability, maintaining vehicle reliability, and carefully balancing innovation with user trust and acceptance. The findings reveal that safety is the most crucial criterion among all stakeholders, which significantly influences both acceptance and trust in AV technology. This emphasis on safety suggests that advancements in AV technology must prioritize the reduction of accidents to gain widespread acceptance.

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Author contributions
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Data availability
The datasets generated during and/or analysed during the current study are available from the corresponding author on reasonable request.

Declarations

Competing interests
The authors have no relevant financial or non-financial interests to disclose. The authors have no competing interests to declare relevant to the content of this article. The authors have no financial or proprietary interests in any material discussed in this article.

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